ROTATING ELECTRIC MACHINE

Technical field

The present invention relates to a rotating electric machine of a type with rotating field circuit, which machine is intended for direct connection to a distribution or transmission network. The invention also relates to the method of monitoring the resistance of the field winding to earth and of determining the rotor temperature.

Background art

The rotating electric machine according to the present invention may be e.g. a synchronous machine, dual-fed machine, asynchronous static current converter cascade, external pole machine or synchronous flow machine.

In order to connect machines of this type to distribution or transmission networks, in the followed called power networks, transformers have previously been used to step up the voltage to the level of the network, i.e. to the range of 130-400 kV.

Generators having a rated voltage of up to 36 kV are described by Paul R. Siedler in an article entitled "36 kV Generators Arise from Insulation Research", Electrical World, 15 October 1932, pages 524-527. These generators comprise windings of high-voltage cable in which the insulation is divided into various layers having different dielectric constants. The insulating material used consists of various combinations of the three components mica-foil-mica, varnish and paper.

It has now been discovered that by manufacturing windings for the machine mentioned in the introduction out of an insulated high-voltage electric conductor with solid insulation of a type similar to cables for power transmission, the voltage of the machine can be increased to such levels that the machine can be connected directly to any power network without an intermediate transformer. A typical operating range for these machines is 30 to 800 kV.

Furthermore, in system solutions based on brushless exciters for excitation of a synchronous machine, for instance, the rotor winding of the synchronous machine is normally not monitored for earth faults.

The object of the present invention is to provide such a rotating electric machine for direct connection to power networks, with the ability to detect earth faults in the rotating field circuit.

Summary of the invention

This object is achieved with a rotating electric machine of the type described in the introductory portion with the characterizing features defined in claim 1.

The insulating conductor or high-voltage cable used in the present invention is flexible and is of the type described in more detail in WO 97/45919 and WO 97/45847. The insulated conductor or cable is described further in WO 97/45918, WO 97/45930 and WO 97/45931.

Thus, in the device in accordance with the invention the windings are preferably of a type corresponding to cables having solid, extruded insulation, like those currently used for power distribution, such as XPLE-cables or cables with EPR-insulation. Such a cable comprises an inner conductor composed of one or more strands, an inner semiconducting layer surrounding the conductor, a solid insulating layer surrounding this inner semiconducting layer and an outer semiconducting layer surrounding the insulating layer. Such cables are flexible, which is an important property in this context since the technology for the machine according to the invention is based primarily on winding systems in which the winding is formed from conductors which are bent during assembly. The flexibility of a XPLE-cable normally corresponds to a radius of curvature of approximately 20 cm for a cable 30 mm in diameter, and a radius of curvature of approximately 65 cm for a cable 80 mm in diameter. In the present application the term “flexible” is used to indicate that the winding is flexible down to a radius of curvature in the order of four times the cable diameter, preferably eight to twelve times the cable diameter.

The winding should be constructed to retain its properties even when it is bent and when it is subjected to thermal or mechanical stress during operation. It is vital that the layers retain their adhesion to each other in this context. The material properties of the layers are decisive here, particularly their elasticity and

relative coefficients of thermal expansion. In a XPLE-cable, for instance, the insulating layer consists of cross-linked, low-density polyethylene, and the semiconducting layers consist of polyethylene with soot and metal particles mixed in. Changes in volume as a result of temperature fluctuations are completely absorbed as changes in radius of the cable and, thanks to the comparatively slight difference between the coefficients of thermal expansion in the layers in relation to the elasticity of these materials, the radial expansion can take place without the adhesion between the layers being lost.

The material combinations stated above should be considered only as examples. Other combinations fulfilling the conditions specified and also the condition of being semiconducting, i.e. having resistivity within the range of 10^{-1}-10^{6} ohm-cm, e.g. 1-500 ohm-cm, or 10-200 ohm-cm, naturally also fall within the scope of the invention.

The insulating layer may consist, for example, of a solid thermoplastic material such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polybutylene (PB), polymethyl pentane (PMP), cross-linked materials such as cross-linked polyethylene (XLPE or PEX), or rubber such as ethylene propylene rubber (EPR) or silicon rubber.

The inner and outer semiconducting layers may be of the same basic material but with particles of conducting material such as soot or metal powder mixed in.

The mechanical properties of these materials, particularly their coefficients of thermal expansion, are affected relatively little by whether soot or metal powder is mixed in or not - at least in the proportions required to achieve the conductivity necessary according to the invention. The insulating layer and the semiconducting layers thus have substantially the same coefficients of thermal expansion.

Ethylene-vinyl-acetate copolymer/nitrile rubber, butylymp polyethylene, ethylene-acrylate-copolymers and ethylene-ethyl-acrylate copolymers may also constitute suitable polymers for the semiconducting layers.

Even when different types of material are used as base in the various layers, it is desirable for their coefficients of thermal expansion to be of the same

order of magnitude. This is the case with the combination of the materials listed above.

The materials listed above have relatively good elasticity, with an E-modulus of E<500 MPa, preferably <200 MPa. The elasticity is sufficient for any minor differences between the coefficients of thermal expansion for the materials in the layers to be absorbed in the radial direction of the elasticity so that no cracks or other damages appear and so that the layers are not released from each other. The material in the layers is elastic, and the adhesion between the layers is at least of the same magnitude as in the weakest of the materials.

The conductivity of the two semiconducting layers is sufficient to substantially equalize the potential along each layer. The conductivity of the outer semiconducting layer is sufficiently large to contain the electrical field in the cable, but at the same time sufficiently small not to give rise to significant losses due to currents induced in the longitudinal direction of the layer.

Thus, each of the two semiconducting layers essentially constitutes one equipotential surface, and the winding with these layers will substantially enclose the electrical field within it.

There is, of course, nothing to prevent one or more additional semiconducting layers being arranged in the insulating layer.

According to advantageous embodiments of the machine in accordance with the invention an excitation system for supplying the field circuit comprises a part rotating with the field circuit, and parts of the detecting circuit for earth faults are arranged in said rotating part. The detecting circuit comprises a rotating injection circuit for application on a measuring circuit that is closed through the impedance between field winding and earth, an injection voltage and a measuring unit for measuring the error current resulting in said measuring circuit from the injection voltage, rectifier units being arranged to form rectified absolute values of the injection voltage and the error current, a wireless communication unit also being provided to transmit said absolute values to a stationary calculating unit for monitoring the resistance of the field winding to earth. This means that only two process signals, namely the rectified absolute values for the injection voltage and the error current, need be transmitted to the stationary part to determine the

resistance value to earth. This results in a limited signal interface between the stationary and the rotating part, with less demand on the slip ring-free transmission. The number of rotating units for injection and measuring is also limited. The calculating unit suitably comprises a computer equipment for implementing requisite calculation algorithms.

According to another advantageous embodiment of the machine in accordance with the invention, in which the excitation system is supplied from an exciter with rotating stator side, the injection circuit is supplied from the rotating stator side of the exciter. Voltage fluctuations can then be compensated for by means of software functions in the computer equipment. These functions are based on known circumstances relating to phase shifting in RC circuits and calculation of both real and imaginary current components and absolute values for limit value determination.

According to yet another advantageous embodiment of the machine in accordance with the invention filter circuits are arranged in said measuring circuit in order to filter away harmonics and to block direct voltages. The filter time constants for filtering harmonics shall in that case correspond to the period time of the injection voltage in order to enable the harmonics to be effectively filtered off.

According to yet another advantageous embodiment of the machine in accordance with the invention scaling units are arranged prior to a comparator for comparison of said absolute values of the error current with predetermined limit values, which scaling units are arranged to normalise and compensate the measured error current for variations in the injection voltage before the error current is supplied to the comparator. This is of significance since the injection voltage is altered with the excitation.

According to another advantageous embodiment of the machine in accordance with the invention the above-mentioned problem is solved by the injection circuit being supplied from a constant voltage source.

According to yet another advantageous embodiment of the machine in accordance with the invention a stationary voltage source is arranged to supply the injection circuit via a ring transformer. This enables earth faults to be detected even when the rotor is stationary.

Brief description of the drawings

To further explain the invention, embodiments of the invention selected by way of example will be described in more detail with reference to the accompanying drawings in which

Figure 1 shows a cross section through the insulated conductor used for windings in the machine according to the invention,

Figure 2 shows a diagram of the excitation system with circuit for detecting earth faults in the field circuit and with means for determining the rotor temperature in an embodiment of the rotating electric machine according to the invention,

Figures 3-6 show equivalent circuits for the measuring circuit included in the detecting circuit for earth faults, in different error cases, and

Figure 7 illustrates an embodiment of a scaling unit for normalising and compensating the measured signal.

Description of preferred embodiments of the invention

Figure 1 shows a cross section through an insulated conductor 11 intended for use in at least one of the windings of the machine in accordance with the invention. The insulated conductor 11 thus comprises a number of strands 35 made of copper (Cu), for instance, and having circular cross section. These strands 35 are arranged in the middle of the insulated conductor 11. Around the strands 35 is a first semiconducting layer 13. Around the first semiconducting layer 13 is an insulating layer 37, e.g. XPLE insulation. Around the insulating layer 37 is a second semiconducting layer 15. The insulated conductor is flexible and this property is retained throughout its service life. Said three layers 13, 37, 15 are such that they adhere to each other even when the insulated conductor is bent. The insulated conductor has a diameter within the interval 20-250 mm and a conducting area within the interval 80-3000 mm^2.

Figure 2 shows a circuit diagram of the excitation system in a rotating electric machine with one or more windings of the insulated conductor shown in Figure 1 to enable direct connection to a power network. The excitation system

comprises both a rotating injection and supply circuit 16 and a stationary unit 20 for detecting earth faults and for calculating the rotor temperature.

The excitation system thus comprises a rotating part 1 equipped with a rotating exciter G3 which, from the rotating stator side, supplies a diode or thyristor bridge 12 which is connected by its direct current side to the field winding 14 of the machine. An injection and measuring circuit 16 is also provided for use when detecting earth faults in the field circuit, and measuring means 18 to determine the field voltage for temperature calculations. The rotating part 1 also includes a supply means 5 to supply the electronic equipment of the rotating part, and also with a communication unit 3. A measuring means 25 is also provided for measuring the field current I_F. Wireless communication between the rotating part 1 and the stationary equipment 20 is achieved with the aid of the communication unit 3 and a stationary communication unit 4.

By means of an injection circuit comprising a transformer 8 for voltage adjustment and galvanic separation, the measuring circuit is supplied with a suitable voltage U via an injection transformer 9, said voltage thus being withdrawn from the AC side of the exciter G3. The measuring circuit includes two parallel RC branches and is closed through the impedance of the field winding 14 to earth. The RC branches serve as current limitation and DC insulation.

The current I generated in the measuring circuit by the injection voltage U is sensed by a sensing circuit 22 via a measuring transformer 11 and converted to a corresponding voltage signal which is filtered in the filter circuit 24 and rectified in the rectifier 26. The voltage signal U_I obtained on the output of the rectifier 26, thus represents the amplitude value for the fundamental tone of the current I in the measuring circuit.

The injection voltage U is also filtered and rectified in similar manner in the filter circuit 28 and the rectifier 30, a voltage signal U_U being obtained on the output of the rectifier, which represents the amplitude value for the fundamental tone of the injection voltage U.

The filter time constants T for the filters 24, 28 shall correspond to the period time of the injection voltage U and measured current I to effectively filter off all harmonics.

The voltage signals U_U, U_l are transmitted by the communication units 3, 4 to the stationary part 20 for calculation of the resistance of the field winding 14 to earth from these signals in the calculating unit 17.

The calculating unit 17 thus enables earth faults in the field winding 14 to be monitored, and an alarm is tripped when the resistance of the field winding 14 to earth falls below a predetermined level.

R_j denotes the resistance of the field winding 14 to earth, i.e. in practice the resistance to the iron mass of the rotating part, and C_j denotes the capacitance of the winding 14 to earth. The resistance R_j may in principle vary from infinitely large to zero.

Figure 3 illustrates an equivalent circuit for the measuring circuit if $R_j = 0$, i.e. the "worst" case with the field winding 14 short-circuited to earth. The resultant current I1 in the circuit can be calculated using known values for the resistance R, capacitance C and injection voltage U, and suitable normalising constants can be determined in accordance with principles described in conjunction with Figure 7 below. The absolute value of the current I1 corresponds to the value of the measured signal U1 that is transmitted to the calculating unit 17, as described above in conjunction with Figure 2.

The diagram to the right of the equivalent circuit in Figure 3 illustrates magnitudes and phase positions of the injection voltage U, composed of a resistive component U_r and a capacitive component U_C, and the current I1.

Figure 4 shows a corresponding equivalent circuit in fault-free state, i.e. the contact resistance to earth is $R_j = \infty$. The capacitance C_j of the winding 14 to earth can be determined using known values for the injection voltage U, resistance R and capacitance C and measuring the current I2.

As in Figure 3, the diagram to the right of the circuit shows magnitudes and phase positions of the injection voltage U, composed of a resistive component U_r in phase with the current I2, and a capacitive component consisting of the voltage drop U_C over the capacitors C and the voltage drop U_j over the capacitance C_j, and the current I2.

Figure 5 shows a corresponding equivalent circuit in the event of a contact resistance between winding 14 and earth R_j, where $0<R_j<\infty$, i.e. a state between the states illustrated in Figures 3 and 4. Different limit values for the current I3 for alarm and tripping can, as mentioned in conjunction with Figure 2, be calculated using known values for the resistances R, capacitances C, earthing capacitance C_j, injection voltage U, and the currents I1 and I2 from the cases shown in Figures 3 and 4, as well as predetermined limit values for the contact resistance to earth R_j.

The impedance Z1 across the two parallel branches, each containing 2R in series with 2C, is thus

$$Z1 = R - J\frac{1}{wC}$$

and the transition impedance between the winding 14 and earth Z2

$$Z2 = \frac{Rj}{1+JwRjCj}$$

the current I3 being obtained from

$$I3 = U/(Z1 + Z2)$$

The diagram to the right of the circuit in Figure 5 illustrates magnitudes and phase positions of voltages and currents in a corresponding manner as in Figures 3 and 4. From this diagram, it is clear that the current I3 is in phase with the current I2 in Figure 4 and includes a current component I_{Cj} through the transition capacitance Cj and a current component I_{rj} through the contact resistance R_j, the latter two current components being at right angles to each other in the diagram, i.e. phase-shifted 90^{o}.

Figures 3 and 5 shows cases with errors on the DC side of the supply to the field winding from the exciter G3, see Figure 2. Figure 6 illustrates a situation with faults on the AC side of the rectifier bridge 12. A fault on the AC side is characterized by the addition of an extra supply source U_{ac}, and by the absolute

value of the current being composed of two components - one driven by the ordinary injection voltage U and one driven by the potential level of the fault point to earth, represented by the voltage U_{ac}. In the event of faults on the AC side, therefore, the total absolute value of the error current will exceed the limit values calculated in the case illustrated in Figure 5 - often by a good margin - resulting in the alarm being tripped.

The corresponding phase diagram to the right in Figure 6 corresponds to that in Figure 5.

In the event of variations in the injection voltage U the measured signals must be compensated by scaling. Alternatively, the predetermined limit values for alarm tripping or releasing, etc. in a comparator must be changed, which is considerably more complicated.

Figure 7 shows a scaling unit 32, 34 included in the calculating unit 17 in Figure 2. In this scaling unit 32, 34 the measured value U_I, representing the absolute value of the current I, is normalised by multiplying it by a normalising constant K1. A suitable magnitude for the normalising constant K1 can be determined by means of a measuring procedure in accordance with Figure 3. Similarly, the measured signal U_U for variations in the injection voltage U is compensated by scaling with a compensation constant K2, wherein $K2=U_U$ at the time of normalising the measured signal U_I. The current I_n, normalised and compensated with regard to variations in the injection voltage U, is supplied to a comparator 38 in which this current I_n is compared with various predetermined limit values Lim 1, Lim 2, Lim 3 for tripping the alarm, emitting a tripping signal. etc.

The measuring means 18 measure the field voltage and the measuring means 25 measures the field current, and corresponding measured signals U_F and I_F are transmitted via the wireless communication units 3, 4 to a unit 40 in the stationary equipment 20 for calculating the rotor temperature from these measured signals, see Figure 2. In the filter 42 in the measuring means 18 the field voltage signal is filtered with a time constant T1 which shall correspond to 0.3 times the no-load time constant of the field winding 14. When the electric machine

is not synchronized on the network, it has a time constant corresponding to the no-load time constant, whereas if the machine is connected to the network this time constant is altered by a factor of approximately 0.3, depending on the inductance of the network.

The unit 40 may in turn be connected to indicating means for the rotor temperature or alarm, for instance, or tripping means to activate these depending on the determined value for the rotor temperature.

Numerous modifications and variations of the embodiments described above are of course possible within the scope of the invention. The invention is thus also applicable to stationary solutions such as static exciters, and the supply voltage to the injection unit can be transformed to the rotating part by means of a ring transformer so that earth faults can also be detected when the machine is stationary.